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Distinguishing B and $\overline{B}$ Hadrons

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Abstract

Distinguishing the flavor of B and $\overline{B}$ hadrons is critical in studies of CP-violation, $B^0 - \overline{B^0}$ mixing, and the underlying b-decay mechanisms. Methods of b "flavor tagging" are broadly divided into "opposite b" tagging and self-tagging of the signal b hadron. The former, while understood, has the perceived drawback of low efficiency. The latter, while having the potential for an order of magnitude higher efficiency, has yet to be demonstrated for neutral B hadrons. In this article we review opposite b tagging in light of methods whose efficacy has only recently been demonstrated or suggested. In addition, we recommend a number of tagging methods for the opposite b including: K^{*0} and $K^{*\pm}$ with large inclusive yields of 15% and 18%; $\overline{\Lambda}$ and $\overline{\Lambda}p$; partially reconstructed charmed hadrons; sophisticated jet charge techniques, etc. We also recommend the use of self-tagging for the *opposite* b hadron. Such an inversion of self-tagging could conceivably increase the efficiency of opposite b tagging and even mitigate the effects of neutral B mixing. Self-tagging of the signal hadron, when possible, could be used either by itself or to confirm the result from the opposite b tag. We suggest that all methods be weighted by their dilutions and combined to yield efficient tagging. For a given detector, this requires that the dilution of each tag be well measured. We therefore review the determination of the dilution D_T for a general tag T in some detail. Finally, we briefly consider CP-violation in the b sector and suggest a number of exclusive modes which can be combined for higher statistics probes of the unitarity angles. While ambitious from an experimental perspective, the program of flavor identification outlined here has the potential to yield important fundamental results in the near future.

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I. INTRODUCTION

Identifying ("tagging") the flavor of beauty hadrons is crucial in studies of CP violation, $B_s - \overline{B_s}$ mixing, and in separating inclusive or exclusive yields of b-hadrons vs. $\bar{b}$-hadrons. This note advocates to weight and combine all conceivable tags in order to optimize the flavor identification of neutral B mesons. For such a program to succeed, the purity (henceforth referred to as dilution) of each tag must be determined. Fortunately, for any experimental setup the dilution for each tag T can be determined from $B^{\pm}T$, primary $\ell^{\pm}T$, and/or $\overset{(-)}{B_d}T$ correlations. Note that we denote as "primary" the lepton coming directly from the decay of the b. These correlations could initially be compared for consistency and, once they are understood, they could be combined to yield a higher statistics measure of dilution for each tag. Studies of b-decay dynamics, of $B_s - \overline{B_s}$ mixing, and of CP violation then become feasible by pairing the relevant mode under study with any available tag T. Consider for instance the CP violating asymmetry of $B_d \rightarrow J/\psi K_S$. Having previously measured dilutions we can correct the asymmetry measurement for the impurities of each tagging method. The sum of available tags T optimizes the measurement of the undiluted asymmetry.

A number of schemes for distinguishing B^0 and $\overline{B}^0$ mesons have been demonstrated or suggested. These include: (i) self-tagging [1–4], (ii) tagging the flavor of the other b in the event [5–8], (iii) jet charge, Q_j, tagging [9,10], and (iv) polarization-tagging [11]. This note explores the first three of these methods. The first identifies the initial flavor of the B meson from the charge of a primary fragmentation hadron produced nearby in phase-space. Throughout this note, we denote a primary hadron as one that originates from the primary interaction vertex, while a primary lepton is a lepton from b-decay and is normally displaced from (i.e. has significant impact parameter with respect to) the primary vertex. Self-tagging suggests that $K^+B_s(K^-\overline{B}_s)$ events could be enhanced over $K^-B_s(K^+\overline{B_s})$ events [3]. Similarly, there could be more $K^*B_s(\overline{K^*}\overline{B}_s)$ than $\overline{K^*}B_s(K^*\overline{B_s})$ events [4], where K^* is either neutral or charged. Ref. [1] predicts an enhancement of $\pi^+B^-(\pi^-B^+)$ over $\pi^-B^-(\pi^+B^+)$ events, and of $\pi^+B_d(\pi^-\overline{B}_d)$ over $\pi^-B_d(\pi^+\overline{B}_d)$ events. The CDF collaboration is in the midst of studying the feasibility of self-tagging [12]. If self-tagging works for neutral B's it could be employed directly to tag the signal B. Even if it does not, it may still work for charged B's. In either case, self-tagging can "literally" be inverted and used effectively to tag the flavor of the opposite b hadron as will be discussed below.

Whereas self-tagging may or may not work, tagging the flavor of the other b-hadron in the event must work in principle. Consider a $b\bar{b}$ event where the $\bar{b}$ hadronizes into a B which is seen in a decay-mode under study, such as $B_d \to J/\psi K_S$, $\pi^+\pi^-$, $B_s \to J/\psi\phi$, $D_s^- l\nu$, $D_s^\pm K^\mp$, $D_s^-\pi^+$, etc. The other b hadronizes into any of many beautiful species $\overline{B}_d$, B^-, $\overline{B}_s$, Λ_b, Ξ_b, etc. The relative mix of beauty hadrons depends upon how the $b\bar{b}$ pair is produced. The production fractions are roughly

$$\overline{B_d} : B^- \approx 0.5 : 0.5 \tag{1.1}$$

for an $e^+e^- \to \Upsilon(4S) \to B\overline{B}$ experiment. And they are

$$\overline{B_d} : B^- : \overline{B_s} : \Lambda_b \approx 0.375 : 0.375 : 0.15 : 0.10 \tag{1.2}$$

for a high energy experiment, $e^+e^- \to Z^0 \to b\bar{b}$ or $p\bar{p} \to b\bar{b} + X \ldots$.

For a given high energy experiment, we denote the mix of the various beautiful species by H_b. H_b *rarely loses b-flavor information due to* $B^0 - \overline{B^0}$ *mixing.* This can be quantified in terms of a dilution parameter D,

$$D \equiv \frac{\text{Prob}(H_{b,phys} \to H_b) - \text{Prob}(H_{b,phys} \to \overline{H}_b)}{\text{Prob}(H_{b,phys} \to H_b) + \text{Prob}(H_{b,phys} \to \overline{H}_b)} \ . \tag{1.3}$$

Here $H_{b,phys}$ denotes a time-evolved, initially pure b-flavored hadron H_b, and $\overline{H}_{b,phys}$ is defined analogously.

The probability of an initial H_b to oscillate into its antiparticle is

$$\begin{aligned} \text{Prob}(H_{b,phys} \to \overline{H}_b) &= f_d \ \text{Prob}(\overline{B}_{d,phys} \to B_d) \\ &\quad + f_s \ \text{Prob}(\overline{B}_{s,phys} \to B_s) \\ &\approx 0.375 \cdot 0.16 + 0.15 \cdot 0.5 \approx 0.13 \ . \end{aligned} \tag{1.4}$$

The production fractions of the various b-species are denoted by $f_u, f_d, f_s, f_{\Lambda_b}$ for $B^-, \overline{B}_d, \overline{B}_s$, and Λ_b. Eq. (1.4) uses the known $B_d - \overline{B_d}$ mixing parameter, and assumes maximal mixing for the B_s meson [9,13]. In addition to a respectable—i.e., large—dilution of

$$D \approx 0.74 \; , \tag{1.5}$$

we stress that almost all decays of H_b are flavor-specific—that is, an "ideal detector" is able to flavor-tag nearly every decay of H_b. The CKM-favored transitions, $b \to c\overline{u}d, c\ell\overline{\nu}, c\overline{c}s$, are generally seen in flavor-specific final states, with only a few exceptions. The first, which has minor effect, is that of CKM-favored transitions of the B^0 which give rise to K_S or K_L final states in which the original b-flavor is lost. In the second, the $b \to c\overline{c}s$ transition of the B_s is not flavor-specific, but this has no effect on the above derivation of D because maximal $B_s - \overline{B_s}$ mixing was assumed.

We remark parenthetically that an ideal detector could study the time-evolution of B^0 modes. Thus, since $B_d - \overline{B_d}$ mixing is known, and $B_s - \overline{B_s}$ mixing will likely be measured in the future, the time-evolution of the flavor-specific modes of the neutral B^0 can be partially disentangled to yield a dilution nearer to unity. It may even be possible to extract partial flavor information from the $b \to c\overline{c}s$ transition of the B_s if it so happens, for example, that the B_s prefers $D_s^{*+}D_s^-$ to $D_s^+D_s^{*-}$ or vice versa.

By setting a substantial lower limit on $B_s - \overline{B_s}$ mixing, $(\Delta m/\Gamma)_{B_s} \gtrsim 9$ [9], it has been recently demonstrated at LEP that the jet charge, Q_j, technique is a formidable tagging tool [10]. The jet charge Q_j is a kinematically weighted average of the charges of particles in each jet. It uses not only the opposite b-jet in the event, but also the signal jet. (Naively, a b-jet starts with a charge of $-1/3$ and is thus more likely to be negatively charged.) An $e^+e^- \to Z^0 \to b\overline{b}$ experiment deals with well balanced b-jets, ideally suited for measuring Q_j. In contrast, at hadron accelerators b-jets are not always well separated (as in the case $g \to b\overline{b}$). In both environments silicon vertex detectors now afford significant additional guidance via the detection and characterization of displaced vertices. The requirement of displaced vertices in jets reduces the mistagging rate of Q_j. To fully optimize jet-charge tagging one should weight displaced tracks differently from the tracks associated to the primary interaction vertex [14]. Further enhancement can be achieved by using any other available discriminating information such as the probability that a given track corresponds to a specific particle type [14]. A sophisticated jet charge algorithm of this type is now under investigation and could become a powerful tagging tool [15].

In contrast to high energy experiments, one could consider a threshold machine $e^+e^- \rightarrow \Upsilon(4S)$. The $\Upsilon(4S)$ is seen in the two-body, p-wave modes; B^+B^- and $B_d\overline{B_d}$. Bose-Einstein statistics forbids a simultaneous $B^0B^0(\overline{B^0}\ \overline{B^0})$ state. Thus, the time of a flavor-specific decay of a neutral B starts the clock for the time evolution of its partner. Time-dependent measurements allow studies of CP violation and are one of the main motivations for asymmetric B-factories at the $\Upsilon(4S)$ [16]. Also at the $\Upsilon(4S)$, tagging the B_d via the flavor of its partner meson works very well in principle [17].

Throughout this note, charge conjugate modes and correlations are implicit, except for the case of CP violation. Extending these ideas to non charge-symmetric initial states, such as pp colliders or fixed target options, is straightforward but the algebra and measurements are more involved and are not discussed here. We do not expect any observable coherence effects at high energy machines, and assume henceforth incoherent $b\bar{b}$ production [18]. Since any detector is imperfect, we have to make do with incomplete information. We therefore advocate to weight and properly combine all conceivable tags. Although the main thrust of this paper is to employ the other b-hadron as a tag, we also consider tags that originate from the signal b-jet itself, such as self-tagging and sophisticated jet charge algorithms. Such a program truly optimizes tagging.

It is important to distinguish between B^0-tagging and tagging-calibrations in which flavor on one side is known (perhaps with some impurity) and flavor tagging efficiency on the other side is being measured. The calibrations are essential to the success of this program as they determine the dilution D_T for each tag and thus allow the correct weighting of individual tags. The determination of dilution for each tag T can be accomplished via several methods, which can serve first as cross-checks and later be combined to yield a more accurate measurement of D_T. The dilution for any tag T can be obtained, for instance, from primary $\ell^{\pm}T$, flavor specific $\overset{(-)}{B_d}\, T$, and $B^{\pm}T$ correlations.

We discuss in some detail possible data samples of charged B's, with which to measure $B^{\pm}T$ correlations. Whereas current $B^{\pm}$ data samples include fully reconstructed $B^{\pm} \to J/\psi K^{\pm}$ events, we suggest the use of the much larger $B^{\pm} \to J/\psi X^{\pm}$ sample where $X^{\pm}$ denotes an odd number of charged tracks associated to the J/ψ vertex. The latter can be required to be significantly displaced from the primary interaction vertex to guarantee b-parentage. Identification of the particles associated to the J/ψ vertex, while helpful, is not strictly necessary since only the charges of the particles are relevant. Missing neutrals—such as K_S, K_L, π^0 or γ— contribute no net charge and hence pose no problem in collecting a $B^{\pm}$ data sample. More than a quarter of the inclusive J/ψ yield in $B^{\pm}$ decays involve a single charge [19,20],

$$B(B^{\pm} \to J/\psi K^{\pm}) = (0.110\ \pm\ 0.015\ \pm\ 0.009)\%\ ,$$

$$B(B^{\pm} \to J/\psi K^{*\pm}) = (0.178\ \pm\ 0.051\ \pm\ 0.023)\%\ ,$$

$$B(B \to J/\psi X) = (1.11\ \pm\ 0.08)\%\ .$$

One could enhance any $B^{\pm}$ data sample by requiring an oppositely charged primary hadron nearby in phase space, if self-tagging works for charged B's [1].

Ideas exist for collecting even more inclusive data samples of b-hadrons [14]. One could for example use $D^{(*)}\ell^- X$ events that are consistent with b-decays or even combine tracks from secondary and tertiary vertices to calculate a vertex mass m' that could distinguish decays of the heaviest charmed hadrons from those of b hadrons by exploiting the expectation that in many cases

$$m'_{\Xi_c^0}\ \ (m'_{\Omega_c})\ \ \lesssim m'_{H_b}\ .$$

The Ω_c appears in parenthesis because its extremely short lifetime helps distinguish it from a much longer lived b-hadron. (For the latter, more speculative ideas the background from collinear $c\bar{c}$ production in such data samples has to be assessed for the case of $p\bar{p}$ colliders.)

We now resume our discussion of calibrations and B^0-tagging experiments. Once calibrations are complete, one may turn to measurements utilizing B^0-tagging. Studies of $B_s - \overline{B_s}$ mixing could become feasible by pairing all flavor specific B_s candidates with any conceivable tag T. CDF reports about a hundred flavor-specific B_s candidates [21]. Studies of CP violation in B^0 decays could also be contemplated.

We cannot overemphasize the importance of good particle identification (p/K/π, lepton, etc. separation) and observation of displaced vertices (including tertiaries in some cases) for tagging purposes. Simple tags based upon such information could be quite effective. If charged, displaced kaons could be well identified, they would provide a powerful tag, with a very large yield in b-decays [6]. Another potent tag would be K^*'s, which also have a large inclusive yield in b-decays. For tagging purposes, it will be advantageous to determine the strangeness content of partially reconstructed charmed hadrons in b-decays, as we will show below. Combining good particle identification and observation of displaced vertices in a sophisticated jet charge algorithm [15] would allow a substantial fraction of all signal B^0-events to be tagged with high purity. Such a program involves an enormous experimental effort but offers the potential reward of the immense riches of B physics and conclusive experimental tests of theoretical speculations.

This note is organized as follows. Primary lepton - tag correlations are the subject of Section II. They yield the dilution for each tag T and the ratio of the inclusive yield of T in b-decay versus $\bar{b}$-decay, by removing $B^0 - \overline{B^0}$ mixing effects. Section III reviews existing lepton - tag correlations from which many tags can be inferred beyond the traditional lepton [5] and charged kaon [6] tags. Alternative tags are enumerated and reviewed. An intense study will seek out and discover many additional and general tags T, such as those based upon particular event topologies [22]. The discovery of new tags could come by observing strong primary $\ell^{\pm}T$, flavor specific $\overset{(-)}{B_d}\ T$, or $B^{\pm}T$ correlations. Section III reviews in detail how to obtain the dilution D_T from $B^{\pm}T$ correlations and also discusses time-dependence of $\overset{(-)}{B^0}\ T$ correlations, which allow $B_s - \overline{B_s}$ mixing and various CP violation studies. Because of its cardinal import, CP violation is the exclusive topic of Section IV. A judicious dilution-weighted combination of all accessible tags, which avoids multiple-counting, could make an ambitious B program feasible. Section V concludes with a bright outlook.

II. LEPTON-TAG CORRELATIONS

This section considers lepton-tag correlations, where the lepton is from one b hadron decay and the tag T generally (but not exclusively) originates from the other b-hadron in the event. At the $\Upsilon(4S)$ one could use a hard lepton (to suppress the background from secondaries, $b \to c \to \ell^+$) and angular correlations between $\ell^\pm$ and T to guarantee that the lepton and tag originate from different B mesons.

A high energy experiment, such as $e^+e^- \to Z^0 \to b\bar{b}$, $p\bar{p} \to b\bar{b} + \ldots$, can use hard, displaced leptons with large transverse momenta, $P_{T,rel}$, relative to their jet to suppress backgrounds. The primary lepton signal is enhanced by pairing it with a displaced vertex from which a few charged prongs emanate such that the overall topology is consistent with being a b-hadron [14]. The tag T could be searched for in the hemisphere opposite to the lepton to avoid collinear $b\bar{b}$ and $c\bar{c}$ backgrounds occurring at hadron colliders. At least one significant background to this primary lepton sample is known and removable, namely $\overline{B} \to DD_s^- X$, where the D provides the wrong sign lepton and the D_s^- is responsible for the displaced vertex.

The first part of this section concerns itself with $\Upsilon(4S)$ experiments, where the removal of $B_d - \overline{B_d}$ mixing effects is discussed. This removal is necessary for extracting the important quantity,

$$L_T \equiv \frac{B(B \to TX)}{B(\overline{B} \to TX)}, \tag{2.1}$$

which separates the inclusive T yield in B decays into relative fractions of B and $\overline{B}$. This information is crucial for understanding the underlying b-decay dynamics, as a recent $\overline{B} \to \Lambda_c X$ measurement amply demonstrated [23,24]. Previous experimental analyses assumed that the inclusive Λ_c yield in B decays is dominated by the $b \to c\bar{u}d$ transition [25], whereas a recent note [23] suggests that, on the contrary, $b \to c\bar{c}s$ is dominant. Neither of the two hypotheses could be ruled out with present data samples [26], except for the recently obtained $\ell^\pm\Lambda_c$ correlations, which show a $b \to c\bar{u}d$ preference with a significant $b \to c\bar{c}s$ component [24]. We therefore advocate that lepton-particle(s) correlations be measured whenever possible. An important aspect of L_T is that it identifies good b-flavor tags.

The latter part of this section discusses correlations at high energy experiments. We again remove $B^0 - \overline{B^0}$ mixing and show how to determine the dilution for each tag T. If the tag T consists of decay daughters of the other b-hadron in the event, then the removal of $B^0 - \overline{B^0}$ mixing effects determines not only the dilution D_T but also the important ratio,

$$I_T \equiv \frac{B(\overline{H}_{b,phys} \to TX)}{B(H_{b,phys} \to TX)}\,. \tag{2.2}$$

I_T measures the relative yield of T in decays of time-evolved $H_{b,phys}$ versus $\overline{H}_{b,phys}$. The dilution D_T can be determined for any tag T, regardless of whether it is a primary hadron, a sophisticated jet charge algorithm, or decay products of the opposite b-hadron in the event. In contrast, the ratio I_T can be extracted only when the tag T consists of decay products of the other b-hadron in the event. The determination of I_T from $\ell^\pm T$ correlations incorporates the fact that the two b hadrons mix independently when produced incoherently at high energy machines.

A. $\Upsilon(4S)$ factory

Consider an $\Upsilon(4S)$ experiment. The removal of $B_d - \overline{B}_d$ mixing requires, in addition to lepton-tag T correlations, measurements of inclusive branching fractions of the B^+ and B^- to T. The latter can be measured for a sample of events in which one B has been fully reconstructed [27] or, in the case of an asymmetric B factory, data in which the charge of one B can be determined even without full reconstruction by exploiting the topological separation of the B and $\overline{B}$ decays. The pairing of the $B^\pm$ data sample with tag T from the other $B^\mp$ in the event determines $B(B^- \to TX)$ and $B(B^+ \to TX)$ separately.

Consider next the reconstructed B^0 and $\overline{B^0}$ data samples involving flavor-specific modes [28]. The measurement of $B(B^0 \rightarrow TX)$ and $B(\overline{B^0} \rightarrow TX)$ requires the removal of $B^0 - \overline{B^0}$ mixing,

$$\frac{N_{B^0 T}}{N_{B^0}} = (1-p)B(\overline{B^0} \rightarrow TX) + p\, B(B^0 \rightarrow TX)\,, \tag{2.3}$$

$$\frac{N_{\overline{B^0} T}}{N_{\overline{B^0}}} = (1-p)B(B^0 \rightarrow TX) + p\, B(\overline{B^0} \rightarrow TX)\,. \tag{2.4}$$

Here p is the probability for a time-evolved, initially pure B^0 to be seen as a $\overline{B^0}$,

$$p \equiv \text{Prob}(B^0_{phys} \rightarrow \overline{B^0}) \approx \frac{x^2}{2(1+x^2)}\,. \tag{2.5}$$

Where in the last equation $\frac{\Delta\Gamma}{\Gamma}$ has been neglected based upon Standard Model estimates, and x is defined as $x \equiv \frac{\Delta m}{\Gamma}$ [13]. The coherence of the $L = 1$, $B^0\overline{B^0}$ state cancels possible interference terms once integrations over the B^0 and $\overline{B^0}$ decay times have been performed, resulting in Eqs. (2.3)-(2.4) [29,30]. Because the fully reconstructed B data sample is rather small, one should use <u>in addition</u> the larger $\ell^{\pm} - T$ sample, which is our next topic.

Theory predicts equal semileptonic widths for the neutral and charged B's, but allows for differences in lifetimes and production rates [31]. The lifetimes and production rates are currently found to be equivalent within 20% experimental uncertainties [9,13,32], and are assumed equal for this note. (It is a trivial exercise to incorporate inequalities once they have been observed.) The probability p is obtained directly from the hard, primary dilepton sample,

$$\frac{p}{2} = \frac{N_{\ell^-\ell^-} + N_{\ell^+\ell^+}}{N_{\ell^-\ell^+} + N_{\ell^-\ell^-} + N_{\ell^+\ell^+}} \tag{2.6}$$

and has a measured value of [13]

$$\frac{p}{2} = 0.079 \pm 0.009\,. \tag{2.7}$$

Numbers of hard, primary leptons from one B paired with tag T from the other B are,

$$N_{\ell^+T} = N_{B\overline{B}}\,\frac{1}{2}\,\alpha_\ell\,\alpha_T\,B(B\to X\ell^+\nu)\Big\{B(B^-\to TX)+ \\ +(1-p)\,B(\overline{B_d}\to TX)+p\,B(B_d\to TX)\Big\}\,, \tag{2.8}$$

$$N_{\ell^-T} = N_{B\overline{B}}\,\frac{1}{2}\,\alpha_\ell\,\alpha_T\,B(B\to X\ell^+\nu)\Big\{B(B^+\to TX)+ \\ +(1-p)\,B(B_d\to TX)+p\,B(\overline{B}_d\to TX)\Big\}\,. \tag{2.9}$$

Here $N_{B\overline{B}}$ denotes the number of $B\overline{B}$ events, while α_ℓ and α_T are the detection efficiency and acceptance factor of hard, primary leptons and T, respectively. Many of the systematic errors cancel in forming the ratio,

$$\frac{N_{\ell^-T}}{N_{\ell^+T}} = \frac{B(B^+\to TX)+(1-p)\,B(B_d\to TX)+p\,B(\overline{B_d}\to TX)}{B(B^-\to TX)+(1-p)\,B(\overline{B_d}\to TX)+p\,B(B_d\to TX)}\,. \tag{2.10}$$

Finally, the largest relevant data sample corresponds to inclusive T in B and $\overline{B}$ decays,

$$R_T \equiv B(B\to TX)+B(\overline{B}\to TX), \tag{2.11}$$

where

$$B(B\to TX)\equiv\frac{B(B^+\to TX)+B(B_d\to TX)}{2}\,, \tag{2.12}$$

$$B(\overline{B}\to TX)\equiv\frac{B(B^-\to TX)+B(\overline{B_d}\to TX)}{2}\,. \tag{2.13}$$

By means of this inclusive T sample, the $\ell^\pm T$ sample, the measurement of p, and the lower statistics measurements of the four separate branching fractions from the fully reconstructed and/or topologically separated B data sample, it is possible to both correctly remove $B^0-\overline{B^0}$ mixing and to determine the four separate branching fractions, $B^+\to TX, B^-\to TX, B_d\to TX$ and $\overline{B_d}\to TX$.

In order to remove $B^0-\overline{B^0}$ mixing from existing $\ell^\pm T$ correlations in the absence of inclusive measurements of $B(B^\pm\to TX)$, we <u>assume</u> the following relationships

$$B(B_d\to TX)=B(B^+\to TX)=B(B\to TX), \tag{2.14}$$

$$B(\overline{B_d} \to TX) = B(B^- \to TX) = B(\overline{B} \to TX), \tag{2.15}$$

resulting in

$$N_{\ell+T} \sim \left(1 - \frac{p}{2}\right)\ B(\overline{B} \to TX) + \frac{p}{2}\ B(B \to TX), \tag{2.16}$$

$$N_{\ell-T} \sim \left(1 - \frac{p}{2}\right)\ B(B \to TX) + \frac{p}{2}\ B(\overline{B} \to TX). \tag{2.17}$$

The ratio L_T is determined from $N_{\ell-T}/N_{\ell+T}$ and the measured value of p. It is a very important quantity, because it probes the underlying B-decay dynamics and determines how well T tags b-flavor.

We stress that the assumptions of Eqs. (2.14)-(2.15) could very well be invalid, as the following two extremes illustrate. The first being the case in which the inclusive yield of tags T is due to $B^{\pm}$ decays only. In that case $N_{\ell-T}/N_{\ell+T}$ determines the ratio L_T without having to correct for any $B_d - \overline{B_d}$ mixing, since

$$N_{\ell+T} \sim\ B(\overline{B} \to TX) =\ B(B^- \to TX)/2,$$

$$N_{\ell-T} \sim\ B(B \to TX) =\ B(B^+ \to TX)/2.$$

The second extreme is the case in which the inclusive T yield arises solely from $\overset{(-)}{B_d}$ decays. In this case the effect of $B_d - \overline{B_d}$ mixing is maximal and must be removed to obtain L_T, since

$$N_{\ell+T} \sim\ (1-p)\ B(\overline{B} \to TX)\ +\ p\ B(B \to TX),$$

$$N_{\ell-T} \sim\ (1-p)\ B(B \to TX)\ +\ p\ B(\overline{B} \to TX).$$

Separate measurements of $B(B^{\pm} \to TX)$ are thus crucial for a correct removal of $B_d - \overline{B_d}$ mixing. In the absence of such $B^{\pm} \to TX$ measurements, theory can be used as a guide. For instance, we predict that Eqs. (2.14)-(2.15) are approximately true for tags T such as the sum of charged and neutral D's, or D_s's. If no guide is available, we suggest to employ the "golden mean" which resides halfway between the two extremes and is precisely Eqs. (2.14)-(2.17).

For sufficiently large $\ell^{\pm}T$ data samples, the understanding of inclusive T yields may be improved by measuring L_T for various momentum bins of T. It is conceivable that T tagging is enhanced in particular momentum ranges and observations of such effects would shed light upon the underlying B-decay mechanism. The quantity L_T can be used for CP studies at an $\Upsilon(4S)$, and is a rather reliable barometer of good b-tags at high energy experiments, barring a few exceptions.

B. High energy experiments

Lepton-tag correlations at high energy experiments determine the dilution of each tag T. As discussed in Section I, the tag need not originate from the other b-hadron in the event. But, if it does, then the $\ell^{\pm}T$ correlations also provide information about the relative fractions of inclusive T production in b-hadron versus $\bar{b}$-hadron decays,

$$I_T \equiv \frac{B(\overline{H}_{b,phys} \to TX)}{B(H_{b,phys} \to TX)} \,. \tag{2.18}$$

The inclusive branching fraction of a time-evolved H_b to T is denoted by

$$\begin{aligned} B(H_{b,phys} \to TX) = f_u\, B(B_u^- \to TX) + \\ + f_d\, B(\overline{B}_{d,phys} \to TX) + f_s\, B(\overline{B}_{s,phys} \to TX) + \\ + f_{\Lambda_b}\, B(\Lambda_b \to TX) + \sum f_I\, B(I \to TX) \;. \\ I = \Xi_b^0, \Xi_b^-, \Omega_b, B_c^- \end{aligned} \tag{2.19}$$

Define $B(\overline{H}_{b,phys} \to TX)$ analogously. The observed number of primary lepton-T correlations is given by

$$\begin{aligned} N_{\ell^+T} &= N_{b\bar{b}}\, \alpha_\ell\, \alpha_T\, B_{s\ell} \Big\{ (1-\chi)\, B\,(H_{b,phys} \to TX) + \chi\, B\left(\overline{H}_{b,phys} \to TX\right) \Big\} \,, \\ N_{\ell^-T} &= N_{b\bar{b}}\, \alpha_\ell\, \alpha_T\, B_{s\ell} \Big\{ (1-\chi)\, B\left(\overline{H}_{b,phys} \to TX\right) + \chi\, B\,(H_{b,phys} \to TX) \Big\} \,, \end{aligned} \tag{2.20}$$

where α_ℓ and α_T are experimental acceptance/efficiency factors for ℓ and T, $N_{b\bar{b}}$ is the number of $b\bar{b}$ events, and $B_{s\ell}$ is the average semileptonic branching ratio for the mixture of b-hadrons H_b. The χ parameter is determined from the dilepton sample, where the two leptons come from different b-hadrons [13],

$$\frac{N_{\ell^+\ell^+} + N_{\ell^-\ell^-}}{N_{\ell^+\ell^-} + N_{\ell^+\ell^+} + N_{\ell^-\ell^-}} = \frac{2\chi(1-\chi)N_u + \left[(1-\chi)^2 + \chi^2\right] N_\ell}{N_u + N_\ell} \tag{2.21}$$

Here $N_u(N_\ell)$ is the predicted unlike-sign (like-sign) dilepton rate in the case of no mixing. Many systematic errors cancel in the ratio N_{ℓ^-T}/N_{ℓ^+T}, which together with χ determines the important quantity I_T,

$$I_T = \frac{\frac{N_{\ell^-T}}{N_{\ell^+T}}(1-\chi) - \chi}{1 - \chi - \frac{N_{\ell^-T}}{N_{\ell^+T}}\chi} \,. \tag{2.22}$$

The dilution for tag T is

$$\begin{aligned} D_T &= \frac{B(H_{b,phys} \to TX) - B(\overline{H}_{b,phys} \to TX)}{B(\overline{H}_{b,phys} \to TX) + B(H_{b,phys} \to TX)} = \\ &= \frac{1 - I_T}{I_T + 1} \,. \end{aligned} \tag{2.23}$$

Note that the dilution for tag T can be determined in more general situations than that indicated by Eq. (2.23). For example, in the case of incoherent $b\overline{b}$ production, one may wish to use self-tagging via primary interaction hadrons or a sophisticated jet charge technique and this can be accomplished via the $\ell^\pm T$ data sample. In such cases however, the result does not provide information about I_T because T does not consist of decay products of the other b-hadron in the event.

The χ parameter is related to the semileptonic branching ratios, $B^d_{s\ell}$ and $B^s_{s\ell}$, of the B_d and B_s mesons by,

$$\chi = \frac{B^d_{s\ell}}{B_{s\ell}} f_d \; Prob(B_{d,phys} \to \overline{B}_d) + \frac{B^s_{s\ell}}{B_{s\ell}} f_s \; Prob(B_{s,phys} \to \overline{B}_s) \,. \tag{2.24}$$

It measures the probability

$$\begin{aligned} Prob(\overline{H}_{b,phys} \to H_b) &= f_d \; Prob(B_{d,phys} \to \overline{B}_d) + \\ &+ f_s \; Prob(B_{s,phys} \to \overline{B}_s) = \chi \,, \end{aligned} \tag{2.25}$$

for the case of equal semileptonic branching ratios of the B_d, B_s and $\overline{H}_b$,

$$B^d_{s\ell} = B^s_{s\ell} = B_{s\ell} \ . \tag{2.26}$$

This section described in detail how to determine the important ratios L_T and I_T, and how to extract the dilution for any tag T. Combining measurements from $\Upsilon(4S)$ and high energy experiments—that is, $N_{\ell-T}/N_{\ell+T}$ and I_T, respectively—singles out information about inclusive production of T in Λ_b and time-evolved $\overline{B}_s$ decays versus $\overline{\Lambda}_b$ and time-evolved B_s decays. The next section applies this formalism to existing $\ell^\pm T$ data samples, and thus informs us about good b-tags.

III. TAGS

As discussed in section I, tagging the flavor of the other b-hadron in the event must work in principle. In this section we consider a wide variety of possible tags. In addition to single particle tags, there exist more general tagging techniques such as jet charge Q_j which has been shown to be a powerful tagging tool in the LEP experiments [10]. To fully optimize jet-charge tagging however, one should weight displaced tracks differently than the tracks associated to the primary interaction since the fragmentation hadrons are expected to be anti-correlated in charge (the basic assumption of self-tagging), while the charge of the final hadrons is correlated to the original B flavor. A sophisticated jet charge algorithm based upon this and other considerations is being developed for use in a hadron accelerator environment and is expected to become a very powerful tagging technique [15]. It improves tagging at e^+e^- colliders as well. Jet charge tagging uses not only the other b-jet in the event, but also the signal b-jet when possible.

The formalism developed in the last section allows one to calculate D_T from existing $\ell^\pm T$ correlations. One can propose other good tags, which can be tested with currently available data sets. Currently all data come from $\Upsilon(4S)$ experiments, but we expect this to change in the near future. Tags need not be restricted to specific particle types but may also be defined by correlating characteristic topologies of one b-jet with the flavor of the other b-hadron in the event. The flavor could be determined for instance, from the primary lepton, from an inclusive $B^{\pm}$ data sample, from an inclusive flavor-specific $\overset{(-)}{B}_d$ data sample, from fully reconstructed b-hadrons, or from topologically separated $B\overline{B}$ events at an asymmetric $\Upsilon(4S)$ machine. Tags at the $\Upsilon(4S)$ are discussed first. High energy experiments should study the effectiveness of all tags mentioned for the $\Upsilon(4S)$, but can also expect additional tags to become available as a result of the incoherence of the $b\overline{b}$ pair, as discussed below.

A. List of tags

Known $\ell^{\pm}T$ correlations at the $\Upsilon(4S)$ are summarized in Table I [24], [33] - [40]. Columns I-VI list the tag particle or particles T, literature references, observed numbers of $\ell^{\pm}T$ correlations (or a proportional quantity), the probability of a wrong lepton-charge assignment $p/2$, and the calculated ratio L_T from Eqs. (2.16)-(2.17). If the $\ell^{\pm}T$ correlation already takes into account the effects of secondaries ($b \to c \to \ell^+$), then only $B^0 - \overline{B^0}$ mixing effects need to be considered, and $p/2 = 0.079 \pm 0.009$. On the other hand, if secondaries have not been dealt with, then we use the ARGUS estimate of $p/2 = 0.14 \pm 0.02$ for ARGUS data where $p_\ell > 1.5$ GeV/c [34]. Effects of secondaries are much smaller for CLEO [41],

$$(p/2)_{secondary} = \left\{ \begin{array}{ll} 0.028 \pm 0.010 & \text{for } \; P_\ell > 1.4 \; GeV/c \\ 0.020 \pm 0.008 & \text{for } \; P_\ell > 1.5 \; GeV/c \end{array} \right\} \tag{3.1}$$

We use those numbers for CLEO results for which all backgrounds were subtracted, except for secondaries and $B_d - \overline{B}_d$ mixing. We do not understand the large discrepancy between ARGUS and CLEO regarding the effects of secondaries and leave it to be sorted out among the two collaborations. We ignore $B_d - \overline{B}_d$ mixing effects upon secondaries, because they are much smaller than the error on secondaries. For future $\ell^{\pm}T$ correlations, one may wish to cut at a higher lepton momentum where secondaries are negligible.

It has been known for many years that primary leptons [5], charged kaons [6] and charmed hadrons from b-decays are good b-tags. Table I reviews the current data on charged kaons and shows that $K^{*-}, \overline{K}^{*0}, D^0, D^{*+}, \Lambda$ [7], Λ_c, and $\Lambda\overline{p}$ identify b-flavor well.

Whereas the ratio L_T determines the cleanliness of tag T, the inclusive yield R_T tells us how copious it is. Table II lists both quantities and shows that K^- is to date the most abundant tag, with an inclusive yield of 0.85 [20]. The inclusive yields of the other tags are 0.15, 0.18, 0.57, 0.24, 0.04, 0.023, 0.06, 0.06 for $\overline{K}^{*0}, K^{*-}, D^0, D^{*+}, \Lambda, \Lambda\overline{p}, \Lambda_c$ and $\overline{p}$ (not from $\overline{\Lambda}$), respectively. Although $\overline{p}$ is not a good tag *per se*, it becomes one once $\overline{p}$ from $\overline{\Lambda}$ are subtracted. This may be welcome news for CP studies at e^+e^- colliders operating at, or slightly above, the $\Upsilon(4S)$, since the same charge of a primary lepton, K or p (not from Λ) tags the B, and one could allow for misidentifications among them.

Table III lists a few more decay daughters of B mesons that are expected to be good flavor tags ($L_T \ll 1$). Correlating them with hard, primary leptons needs yet to be performed. Some of them are copiously produced in B decays. The respective yields of $D^+, D_s^-, \Xi_c^0, \Xi_c^+$ and Ξ^- are 0.25, 0.12, 0.02, 0.02, 0.003 [20]. Due to large uncertainties in the absolute branching fractions of the modes in which the $\Lambda_c, D_s^-, \Xi_c^0$ and Ξ_c^+ are seen, their inclusive yields in B decays could differ sizably from the values listed in Tables II and III. Theoretical considerations lead us to suspect that the Λ_c and D_s^- yields in B decays may well be significantly underestimated in Tables II - III. Elevated yields of charmed hadrons in B decays would resolve the so-called semileptonic branching fraction puzzle of the B mesons [42].

A sizable fraction of charged hyperons may live long enough to be detected via dE/dx without full reconstruction [14]. Whereas the Ξ^- and Ω^- are probably good tags, the situation pertaining to Σ's is less clear [43]. Because dE/dx is not able to discriminate among the various charged hyperon species, experimental studies will be necessary to determine the effectiveness of this tag.

We predict that most D_s^- come from the virtual W with charge opposite to that of most charged D's in $\overline{B}$ decays. A simple tag based, for example, upon the charge of the tertiary vertex will therefore not succeed because of similar inclusive production rates of D_s^- and D^+ in $\overline{B}$ decays. One could however discriminate inclusively between these charmed hadrons in at least three ways. First, the D_s lifetime is 2.3 times shorter than that of the D^+. Second, the momentum spectra of the two charmed mesons differ [20]. In B decays, the $D_s^{(*)}$ is generically produced in association with another charmed meson and is seen in two body modes about 50 percent of the time [44], in contrast to the D mesons. Whereas the spectrum of the D_s is peaked at high momenta, that of the D meson is much flatter [20,44]. Third, K/π separation discriminates between the two charmed mesons because the D_s^+ is mainly seen in $S = 0$ final states containing an even number of kaons whereas the D^+ decays mainly in $S = -1$ final states containing an odd number of kaons. One has to take into account, however, that the Cabibbo-suppressed modes are anomalously large for the D^+.

Further, consider a displaced vertex with a few charged tracks which is consistent with being a charmed meson (or even a Λ_c^+). If two of the tracks satisfy a ϕ hypothesis, then it is probable that the parent is a D_s, with charge determined from the other track(s). The inclusive yield of ϕ in D_s decays is quite enhanced over that in D^+ and D^0 decays [45]. If no two tracks satisfy the ϕ hypothesis, one could search for a $\overline{K}^{*0}$ analogously. The inclusive yield of $\overline{K}^{*0}$ in D meson decays dominates that of D_s^+ decays [45]. Thus, $\overline{K}^{*0}$ would tag b-flavor well. A systematic study of all such correlations is currently underway and will likely enlarge future data samples [22]. Clearly, it will be useful for experiments to measure the inclusive yields of $\phi, \overline{K}^{*0}, K^{*0}, K^{*-}, K^{*+}$ in D_s^+, D^+, D^0, and Λ_c decays.

Pions are by far the most copious type of charged particles in B decays with an average multiplicity of about 4 per B decay [20]. Thus, any characteristic of a charged π (momentum, $P_{T,rel}$, etc.) from one b which can be found to exhibit a strong correlation with the charge of the hard, primary lepton from the semileptonic decay of a partner b could also be employed as a tag. Such characteristics could also be searched for in the data sample where one B has been either fully reconstructed or spatially disentangled.

At least in the case of the $\overline{p}$, it is possible to turn a bad tag with $L_T \approx 1$, into a good one. For instance, a $T = \overline{p}$ may become a better tag when associated with a K^+ or π^+ from the same T vertex. Recall that a $\overline{p}$ becomes a great tag when associated with a Λ. One could try and make particle associations for other marginal tags or one could measure L_T as a function of momentum to see if there exists a momentum range in which T tags the b-flavor much better. At an asymmetric $\Upsilon(4S)$ factory and at high energy experiments the purity of single particle tags is generally enhanced by demanding that they originate from displaced vertices. We would like to reiterate however that not only single particle tags should be used, but any conceivable event topology should be studied for strong correlations with b-flavor. We are confident that such a program will find many additional tags.

While most good tags at the $\Upsilon(4S)$ remain good ones (and some even become better ones) at high energy experiments and should be vigorously investigated, there are exceptions, such as D_s^- and $\overline{p}$ (not from $\overline{\Lambda}$). As mentioned above, additional selection criteria may be able to turn even the exceptions into usable tags. At the $\Upsilon(4S)$, only the $B^{\pm}$ and $\overset{(-)}{B}_d$ species are created and D_s^- for these cases originates mainly from virtual $W \rightarrow \overline{c}s$ decays, with an inclusive yield of 12%. In contrast, the $b \rightarrow c$ transition—responsible for almost all b-decays—governs the inclusive D_s^+ production in $\overline{B}_s$ decays at high energy experiments. There is an additional contribution of about ten percent from oppositely charged D_s^- originating from virtual $W \rightarrow \overline{c}s$ decays. Because of the expected production fraction of B_s mesons, the yields of D_s's from the virtual $W \rightarrow \overline{c}s$ and from the $b \rightarrow c$ transition are comparable and the large $B_s - \overline{B_s}$ mixing washes out the initial flavor information. Consequently, the $D_s^{\pm}$ tags are not as clean as at the $\Upsilon(4S)$, because of the $\overset{(-)}{B}_s \rightarrow D_s^{\pm} X$ background. However, separating D_s originating from $W \rightarrow \overline{c}s$ versus $b \rightarrow c$ decays may still be possible due to their different momentum spectra. The D_s^+ momentum spectrum for D_s^+ coming from the $b \rightarrow c$ transition is expected to be similar to that of the D meson in $\overline{B}$ decays—that is, much flatter than the high momentum-peaked spectrum of D_s originating from the virtual W [20].

A potentially more severe problem exists for the prompt proton (i.e. not from Λ), in b-decays. If one were able to separate the yield of "prompt protons" into those from B-mesons and those from Λ_b's, then the two yields could be used as good tags. Indiscriminate use of p (not from Λ) will not tag b-flavor well. We know of no ingenious method to accomplish this and can offer only a couple of, at best, marginal suggestions. One is to seek an additional antiproton. Distinguishig $p\overline{p}X$ events from pX events may allow one to enrich the p from Λ_b data sample. Alternatively, perhaps the momentum spectrum of the prompt protons discriminates between the two b-sources. Lastly, one could try to exploit the slight difference in the lifetime of Λ_b's ($\sim 1.2ps$) versus B-mesons ($\sim 1.6ps$) [9]. Regardless of whether or not detached protons are good tags, they could be used as a potent b-trigger [22]. Their inclusive yield in b-decays is substantial, and the background from charmed baryons can be disentangled due to their much shorter lifetimes.

High energy experiments could identify the b-flavor using a sophisticated jet-charge Q_j [15]. They could unambiguously determine the flavor of the accompanying b-hadron, either from its charge $B^{\pm}$ or from it being a b-baryon versus $\bar{b}$-baryon [8]. Self-tagging may be able to distinguish a B from a $\overline{B}$ by correlating the beauty meson with the charge of a primary hadron nearby in phase space [1,2]. If self-tagging were to work for neutral B's it could be applied directly to signal B hadrons. Even if it does not work for neutral B's, it may work for charged B's, in which case the self-tagging scheme could be turned "literally" upside-down to tag a signal B hadron via the charge of a primary hadron found in a small cone about the axis of a jet opposite to it. This works well for $Z^0 \to b\bar{b}$ where the two b-jets are generically back to back, but probably needs to be augmented for $p\overline{p} \to b\overline{b} + \ldots$, by requiring a displaced vertex to define the opposite jet [15]. This primary hadron tag could then be combined with other information to augment the tag. For instance, identifying the charge of the other $B^{\pm}$ could be enhanced by correlating it with the opposite charge of a primary hadron nearby its phase space. Experiments will determine the optimal tags which combine information from the other b-jet with a primary hadron nearby its phase space. This is in fact an example of a more general and sophisticated jet charge tag.

There are many promising event topologies for tagging which can be identified by a systematic analysis of inclusive b-decays. Since almost all b-decays involve the $b \to c$ transition, their detailed understanding requires extensive knowledge of charmed hadron decays. We have therefore been studying all aspects of charm decays, such as inclusive decays, exclusive decays, and theoretical constructs and these will be reported elsewhere, when a thorough analysis has been completed [22]. Here we restrict ourselves to a few examples. For a $2d$ ($3d$) vertex detector, one possible event topology could be a detached vertex with 3 (2) or more charged tracks. Suppose that neither leptons nor protons are seen and that the vertex is consistent with having been formed by a charmed hadron decay. The number of kaons in the event then discriminates between D^+, D^0 and D_s^+. Good particle identification would make this information accessible to an experimentalist. In the absence of clean particle identification, one could weight tracks by the probability that they correspond to a given particle type. Such a vertex could also arise from decays involving a lepton. For example,

$$\overline{B} \to D^{*+} \left[\to \pi^+ D^0 \left(\to K^- \pi^+ X\right)\right] \ell^- X \text{ or}$$

$$\overline{B} \to D^0(\to K^- \pi^+ X) \ell^- X,$$

where the short D^0 lifetime would likely result in a merging of the tertiary D^0 vertex with the secondary b decay vertex. (Future high resolution experiments could separate the tertiary from the secondary vertices to enhance tagging.) Of course, the charge of the lepton as well as that of the kaon correlate well with the b-flavor.

Another event topology could be a displaced lepton which does not associate with a 3 (2) or more charged track vertex consistent with a charmed hadron [14]. The charge of the lepton would be a good b-tag, and the other vertex could reveal information upon the nature of the charmed hadron that could be used to corroborate the lepton tag. The vertex mass technique discussed in Section I could be turned into a tag by utilizing the probabilities of particle identifications, the charge of the partially reconstructed b-hadron, and any other available, discriminating information in the event. Further, it has been suggested that it may be possible to accumulate large inclusive b hadron data samples [14] without requiring leptons in the final state by selecting dijet events with displaced vertices in both jets together with some minimal requirement to reject charm (such as vertex mass discussed above). Such samples could be an interesting source for a variety of studies of non-leptonic b decays.

Although quite a few tagging schemes have been discussed, we are confident that an intense study would find many more usable tags for any given detector. Clearly, to optimize tagging, we advocate a judicious dilution weighted combination (which avoids multiple counting) of all usable tags. This implies a well understood dilution for each tag T, which fortunately can always be determined from either $\ell^{\pm}T$ (last section) or $TB^{\pm}$ correlations to which we now turn.

B. $TB^{\pm}$ correlations

Consider incoherent production of $b\bar{b}$ events at a high energy experiment. Define the number of $B^{\pm}$ events correlated with a given tag T or $\overline{T}$ by [47]

$$\begin{aligned} P_1 &\equiv N(TB^{+}) \,, \quad P_2 \equiv N(TB^{-}) \,. \\ P_3 &\equiv N(\overline{T}B^{-}) \,, \quad P_4 \equiv N(\overline{T}B^{+}) \,. \end{aligned} \tag{3.2}$$

Statistics can be doubled, because for charge symmetric production of $b\bar{b}$ events—as in $p\bar{p} \to b\bar{b} + \cdots$ or $e^+e^- \to Z^0 \to b\bar{b}$—we get

$$P_1 = P_3 \,, \quad P_2 = P_4 \,. \tag{3.3}$$

As for inclusive $B^{\pm}$ data samples, a few suggestions were mentioned in Section I, which we repeat here.

One could use the displaced J/ψ data sample paired with an odd number of charged prongs originating from the same J/ψ vertex. The detached J/ψ guarantees b-parentage. No particle identification is required, and missing neutrals pose no problem. This is a clear $B^{\pm}$ data sample. Alternatively one could use $D^{(*)}\ell^{-}X$ events that are consistent with coming from a b-decay or the fully hadronic sample mentioned above. (For the latter two however the backgrounds due to collinear $c\bar{c}$ production at hadron machines must be taken into account.) If self-tagging works for charged B's, one may wish to pair the charged $B^{\pm}$ data sample with oppositely charged hadrons nearby in phase space to reduce backgrounds. The dilution of tag T is

$$D_T = \frac{P_1 - P_2}{P_1 + P_2} \tag{3.4}$$

and could be checked against the result obtained from $\ell^{\pm}T$ correlations (see Section II). (Of course, when the tag T consists of decay products of the other (non signal) b-hadron, the $TB^{\pm}$ correlations determine again I_T.) Further cross-checks for D_T involve the smaller samples of fully reconstructed $B^{\pm}$, such as $B^{\pm} \to J/\psi K^{\pm}, J/\psi K^{*\pm}$, and flavor-specific $\overset{(-)}{B_d}$. Assuming incoherence, the same dilution occurs for the neutral B^0 mesons (B_d or B_s), once $B^0 - \overline{B^0}$ mixing has been removed, i.e.,

$$
\begin{aligned}
N(TB^0) &\sim P_1 \,, \ N(T\overline{B^0}) \sim P_2 \\
N(\overline{T}\,\overline{B^0}) &\sim P_3 \,, \ N(\overline{T}B^0) \sim P_4.
\end{aligned}
\tag{3.5}
$$

Here B^0 and $\overline{B^0}$ indicate the initial flavor of the neutral B prior to mixing. This fact allows one to compare D_T measurements from a variety of data samples involving B_d mesons. It also allows one to measure $B_s - \overline{B}_s$ mixing and to study CP violation, which will be the topic of the next section.

Consider flavor-specific modes of neutral B mesons, such as

$$B_d \to J/\psi K^{*0},\ \overline{D}^{(*)}\ell^+X, D^{(*)-}\pi^+, \overline{D}^{(*)}X_{u\bar{d}},$$

$$\overline{B}_d \to J/\psi \overline{K}^{*0},\ D^{(*)}\ell^-X\ ,\ D^{(*)+}\pi^-\ ,\ D^{(*)}\overline{X}_{u\bar{d}},$$

$$B_s \to D_s^-\ell^+X, J/\psi\overline{K}^{*0}, D_s^-\pi^+, D_s^-X_{u\bar{d}},$$

$$\overline{B}_s \to D_s^+\ell^-X,\ \ J/\psi K^{*0}\ , D_s^+\pi^-, D_s^+\overline{X}_{u\bar{d}},$$

where the flavor of $K^{*0}(\overline{K}^{*0})$ is identified by the charge of their charged daughter-kaon. The symbol $X_{u\bar{d}}$ represents a collection of particles with zero strangeness, such that the only consistent underlying quark-transition for $\overline{D}^{(*)}X_{u\bar{d}}$ and/or $D_s^-X_{u\bar{d}}$ final states is $\bar{b} \to \bar{c}u\bar{d}$ and not $\bar{b} \to \bar{c}c\bar{s}$. Define a "right-sign" combination as either TB^0 or $\overline{T}\,\overline{B}^0$, and a "wrong-sign" combination by $T\overline{B}^0$ or $\overline{T}B^0$. The time-dependence of the relative numbers of the right-sign R and wrong-sign W combinations are [47]:

$$
\begin{aligned}
R(t) &= e^{-\Gamma t}\left\{P_1\cos^2\frac{\Delta mt}{2} + P_2\sin^2\frac{\Delta mt}{2}\right\}, \\
W(t) &= e^{-\Gamma t}\left\{P_1\sin^2\frac{\Delta mt}{2} + P_2\cos^2\frac{\Delta mt}{2}\right\}.
\end{aligned}
\tag{3.6}
$$

The time-dependent asymmetry is then

$$\frac{R(t) - W(t)}{R(t) + W(t)} = D_T \cos \Delta m t \ , \tag{3.7}$$

which integrates to

$$\frac{\int dt \ [R(t) - W(t)]}{\int dt \ [R(t) + W(t)]} = D_T \, \frac{1}{1 + x^2} \ , \tag{3.8}$$

with

$$x \equiv (\Delta m / \Gamma)_{B^0} \ . \tag{3.9}$$

(Note that the above equations assume equal lifetimes for the heavy and light mass eigenstates of B^0 which is an excellent approximation for the B_d-system, but may be violated at the 10-20% level for the B_s-system [48].)

Since $B_d - \overline{B}_d$ mixing is known [13], $x_d = 0.71 \pm 0.07$, Eqs. (3.7) - (3.8) imply that dilutions D_T can also be measured with flavor-specific B_d- modes (both time-dependent and time-integrated). Furthermore $B_s - \overline{B}_s$ mixing could, for instance, be measured via the time-evolution of flavor specific modes of B_s correlated with tags T.

Finally, suppose that in general one were to identify a particularly clean and copious tag T', where the dilution $D_{T'}$ is known from either $\ell^\pm T'$ or $B^\pm T'$ or flavor-specific $\overset{(-)}{B}_d \, T'$ correlations or any combination thereof. Then, D_T for some other tag T could be determined from $T\overline{T}'$ and TT' correlations. The most accurate determination of D_T is obtained by correctly weighting and combining all known $T \ \overset{(-)}{T}{}', TB^\pm$, flavor specific $\overset{(-)}{B}_d \ T$ and $\ell^\pm T$ correlations.

We know that tagging the flavor of the other (non signal) b-hadron in the event must work in principle. We discussed many possible tags and recommended that one seek and find event topologies that can be used as tags. The dilution for any tag D_T can be determined from $B^\pm T$ correlations. It is also obtained from primary lepton-tag correlations and $\overset{(-)}{B}_d \ T$ data samples, which could serve as cross-checks and be combined for a more accurate final determination. The correct dilution weighted combination of all possible tags (which avoids multiple counting) optimizes tagging. It allows studies of $B_s - \overline{B}_s$ mixing by measuring for instance the time-evolution of flavor-specific B_s modes. It also allows CP studies to be contemplated which is the topic of Section IV.

IV. CP VIOLATION

Of central importance is the measurement of CP violation and the clean extraction of the weak phases, to which we now turn. We denoted by B^0_{phys} a time-evolved state which was initially pure B^0,

$$|B^0_{phys}(t=0)\rangle = |B^0\rangle \ . \tag{4.1}$$

$\overline{B}^0_{phys}$ was defined analogously. Consider the case where the neutral B is seen in a CP-eigenstate f, such as $B_d \to J/\psi K_S, \pi^+\pi^-, B_s \to D_s^+ D_s^-, J/\psi\phi$ [49]. The time-dependent or time-integrated CP-violation asymmetry is given by

$$A_f \equiv \frac{\Gamma(B^0_{phys} \to f) - \Gamma(\overline{B}^0_{phys} \to f)}{\Gamma(B^0_{phys} \to f) + \Gamma(\overline{B}^0_{phys} \to f)} \ , \tag{4.2}$$

where the time-dependent widths are

$$\overset{(-)}{\Gamma}(t) \equiv \Gamma(\overset{(-)}{B^0_{phys}}(t) \to f) \sim e^{-\Gamma t}\left\{1 \overset{(+)}{-} Im\lambda \ \sin \ \Delta m t\right\} . \tag{4.3}$$

Table IV lists the interference terms $Im\lambda$ in terms of the angles of the CKM unitarity triangle [50]. The $J/\psi K_S$ asymmetry determines $\sin 2\beta$, and $\pi^+\pi^-$ determines $\sin 2\alpha$ if penguin diagrams can be neglected. The $B_s \to J/\psi\phi$ asymmetry measures the angle γ once $| V_{ub}/V_{cb} |$ is known [51]. The time-integrated asymmetry is

$$A_f = \frac{\int dt \left[\Gamma(t) - \overline{\Gamma}(t)\right]}{\int dt \left[\Gamma(t) + \overline{\Gamma}(t)\right]} = \frac{-x}{1+x^2} Im\lambda \ . \tag{4.4}$$

Time-dependence is not crucial for the B_d meson ($x \approx 0.7$), while it is crucial for the B_s meson, where $x \gg 1$ is expected [13,52] and observed [9]. Several experiments will be able to study time-evolution, which therefore should be done. The time-dependent asymmetry is

$$A_f(t) \; = \; \frac{\Gamma(t) - \overline{\Gamma}(t)}{\Gamma(t) + \overline{\Gamma}(t)} = -Im\lambda \; \sin(\Delta m t) \; . \tag{4.5}$$

Our imperfect knowledge of the initial b-flavor introduces dilution D_T. Correlating the neutral B mode f with tag T, we obtain the observed asymmetry,

$$A_f^T \equiv \frac{N(T,f) - N(\overline{T},f)}{N(T,f) + N(\overline{T},f)} \; . \tag{4.6}$$

It is related to the true asymmetry A_f by

$$A_f^T = D_T \;\; A_f \; , \tag{4.7}$$

which holds for both time-dependent and time-integrated studies. Whereas the true asymmetry A_f is independent of the tag T, the observed asymmetry A_f^T and dilution D_T depend on T. The correct dilution weighted combination of all accessible tags T optimizes the measurement of the true asymmetry A_f, and hence of the interference term $Im\lambda$ which determines the relevant weak phase.

Many exclusive modes measure the same unitarity angle within the CKM (Cabibbo-Kobayashi-Maskawa) model of CP violation [53]. They can be added to increase statistics. The addition must be done carefully lest a partial cancellation of the asymmetry due to CP-even and CP-odd modes [54] makes the extraction of the relevant unitarity angle less crisp. For instance, the angle β can be determined also from

$$B_d \rightarrow J/\psi K^{*0}(\rightarrow \pi^0 K_S), J/\psi \rho^0, J/\psi \omega, \;\; [55,56] \tag{4.8}$$

$$B_d \rightarrow D\overline{D}, D^*\overline{D}, D\overline{D}^*, D^*\overline{D}^*, \;\; [57\text{–}59] \tag{4.9}$$

$$\text{and} \qquad B_d \rightarrow \overline{D}^0(\rightarrow f_{CP}) X_{u\bar{d}} \; , \;\; [60]. \tag{4.10}$$

Here $X_{u\bar{d}}$ denotes a collection of particles which guarantee that the $B_d \rightarrow \overline{D}^0(\rightarrow f_{CP})X_{u\bar{d}}$ process is by far dominated by the underlying $\bar{b} \rightarrow \bar{c}u\bar{d}$ quark transition. The symbol f_{CP} stands for D^0 decay modes which are either CP eigenstates or which can be decomposed into

CP eigenstates. For example, the decomposition can be accomplished through an angular correlation study [56], such as for $D^0 \to \rho^0 \overline{K}^{*0} (\to K_S \pi^0)$. The summation of all of these exclusive modes may well provide the necessary increase in statistics to rule out or observe CP violation in the CKM model. Once sufficient statistics have been accumulated one may wish to undertake precision studies of the CKM model by studying the CP-violating asymmetries for each of the underlying quark-subprocesses separately.

Some CP-noneigenstates, such as $B_s \to D_s^\pm K^\mp$ [61], $\overset{(-)}{D^0}\ \phi$ [62], are expected to show large time-dependent CP-violation effects and allow a clean extraction of the CKM unitarity angle γ. The formalism developed for CP-eigenstates can be trivially extended to include the case of non-CP eigenstates [61,58,2]. The algebra though will be more cumbersome.

V. SUMMARY

Distinguishing B from $\overline{B}$ is crucial to a deeper understanding of nature. Studies of CP violation, $B_s - \overline{B}_s$ mixing, and measuring the production fraction of flavor tags T from b-hadrons versus $\bar{b}$-hadrons becomes possible when B and $\overline{B}$ can be distinguished. In principle, tagging the flavor of the other b in the event achieves this goal.

An "ideal detector" could use almost any b-decay as a flavor tag with an overall dilution of

$$D \equiv \frac{\mathrm{Prob}(H_{b,phys} \to H_b) - \mathrm{Prob}(H_{b,phys} \to \overline{H}_b)}{\mathrm{Prob}(H_{b,phys} \to H_b) + \mathrm{Prob}(H_{b,phys} \to \overline{H}_b)} \approx 0.74 \,. \tag{5.1}$$

The existing $\Upsilon(4S)$ data on charged, primary $\ell^\pm T$ correlations—where one B gives rise to the lepton and the other to T—identifies many good tags. We have discussed in detail the correct removal of $B_d - \overline{B}_d$ mixing effects.

After removing $B_d - \overline{B}_d$ mixing, we calculated the important ratio L_T. Because L_T and I_T are crucial for a deeper understanding of b-decay mechanisms, we recommend $\ell^\pm T$ correlation be measured whenever possible, both at $\Upsilon(4S)$ factories and at high energy machines. We determined the ratio I_T from $\ell^\pm T$ correlations at higher energy machines, where $b\bar{b}$ production is incoherent. Because the probability of a time-evolved H_b to be seen as its antiparticle is small $Prob(H_{b,phys} \to \overline{H}_b) \approx 0.13$, the ratio I_T tells one about the relative strength of the inclusive yield of tags T from $\bar{b}$-hadrons versus b-hadrons. The dilution D_T of each tag can be determined from $\ell^{\pm}T$ correlations, and also from $TB^{\pm}$ correlations. The $B^{\pm}$ data sample could be simply $J/\psi X^{\pm}$ events, where the J/ψ is displaced and $X^{\pm}$ is a collection of charged particles originating from the J/ψ vertex.

One should use all conceivable tags, properly weighted and combined, and not restrict oneself to traditional primary leptons and $K^{\pm}$'s. An optimal tagging scheme uses all available information for a given b decay to weight and sum charges and particle identification probabilities (and any other pertinent information), using different weights for displaced particles than for primary hadrons [14]. Section III lists many tagging possibilities, and many more will be presented once a systematic analysis has been completed [22].

Clearly, one must develop an intimate knowledge of one's detector and understand its capabilities and limitations, in order to determine all possible tags and their dilutions D_T. Once this is accomplished, the study of CP-violation, of $B_s - \overline{B}_s$ mixing and the determination of I_T could be simple exercises in combining correctly all possible tags correlated with the relevant signal. It is a challenge worth accepting.

After completion of this report, we learnt about Ref. [63] which is of interest to the reader and partially overlaps with an independent analysis [15].

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$$B(D_s^+ \to \phi X) \gtrsim 17.1\%, \quad B(D^+ \to \phi X) \gtrsim 3.0\%, \quad B(D^0 \to \phi X) \gtrsim 1.1\%.$$

As to date, most of the ϕ yield in D^0 decay comes from the $\phi\overline{K}^0$ mode. The $\overline{K}^0$ will not decay at the ϕ vertex. Subtracting this non-prompt contribution leaves us with the prompt signal,

$$B(D^0 \to \phi X) \gtrsim 0.26\%.$$

The situation for K^{*0} is

$$B(D^+ \to \overline{K}^{*0}X) \gtrsim 24.3\%, \quad B(D^+ \to K^{*0}X) \gtrsim 0\%,$$

$$B(D^0 \to \overline{K}^{*0}X) \gtrsim 9.0\%, \quad B(D^0 \to K^{*0}X) \gtrsim 0.3\%,$$

$$B(D_s^+ \to \overline{K}^{*0}X) \gtrsim 8.9\%, \quad B(D_s^+ \to K^{*0}X) \gtrsim 0\%,$$

$$B(\Lambda_c^+ \to \overline{K}^{*0}X) \gtrsim 1.6\%, \quad B(\Lambda_c^+ \to K^{*0}X) \gtrsim 0\%.$$

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TABLES

TABLE I. Primary lepton-tag correlations. Columns I-VI list the tag T, reference, observed number of $\ell^{\pm}T$ correlations (or a proportional quantity), the probability of wrong lepton-charge assignment $p/2$, and the calculated ratio L_T.

T	References	N_{ℓ^+T}	N_{ℓ^-T}	$p/2$	$L_T \equiv \frac{\Gamma(B\to TX)}{\Gamma(\overline{B}\to TX)}$
Λ	CLEO [33]	103.0 ± 12.1	31.4 ± 8.2	0.11 ± 0.01	0.19 ± 0.09
Λ	ARGUS [34]	55±13	30±10	0.14 ±0.02	0.42 ± 0.26
K^-	CLEO [35,36]	0.66 ± 0.05 ±0.07	0.19 ±0.05±0.02	0.10 ±0.01	0.18 ±0.09
K^-	ARGUS [37,38]	0.620 ±0.013±0.038	0.165±0.011±0.036	0.079±0.009	0.18±0.07
$\overline{K}^{*0}$	ARGUS [37]	0.143±0.019±0.012	0.014±0.021±0.011	0.079±0.009	0.01±0.17
K^{*-}	ARGUS [37]	0.169±0.056±0.036	0.015±0.049±0.027	0.079±0.009	0.00±0.34
D^{*+}	ARGUS [39]	28.2±6.1±0.9	5.5±4.0±1.2	0.079±0.009	0.11±0.16
D^0	CLEO [40]	0.74 ± 0.20	0.18±0.21	0.10±0.01	0.14±0.30
$\overline{p}$	ARGUS [34]	453 ±34	333±34	0.14±0.02	0.65±0.12
$\Lambda\overline{p}$	ARGUS [34]	27±6	4.5±3.5	0.14±0.02	0.00±0.14
Λ_c	CLEO [24]	139 ± 16	38±16	0.075±0.016	0.20±0.13±0.04

TABLE II. Inclusive yields in B decays [20] and their fractional yields from B versus $\overline{B}$ mesons.

T(tag)	$L_T \equiv \frac{B(B\to TX)}{B(\overline{B}\to TX)}$	$R_T \equiv B(B \to TX) + B(\overline{B} \to TX)$
K^-	0.18±0.07	0.85±0.07±0.09
		Multiplicity: 0.78±0.02±0.03
$\overline{K}^{*0}$	0.01±0.17	Multiplicity: 0.146±0.016±0.020
K^{*-}	0.00±0.34	Multiplicity: 0.182±0.054±0.024
Λ	(CLEO value) 0.19±0.09	0.040±0.005
$\Lambda\overline{p}$	0.00±0.14	0.023±0.004±0.003
D^{*+}	0.11±0.16	0.237±0.023±0.009
$\overline{p}$	0.65±0.12	0.08±0.005
D^0	0.14±0.30	0.567±0.040±0.023
$\overline{p}$(not from $\overline{\Lambda}$)	0.22±0.12	0.056±0.007
Λ_c	0.20±0.13±0.04	0.064±0.013±0.019

TABLE III. Expected good tags $T(L_T \ll 1)$ and their inclusive yields in B decays.

T(tag)	Ref.	$R_T \equiv B(B \to TX) + B(\overline{B} \to TX)$ [in %]
D_s^-	[44]	11.81 ±0.43±0.94
D^+	[20]	24.6±3.1±2.5
Ξ_c^+	[24]	1.5±0.7
Ξ_c^0	[24]	2.4±1.3
Ξ^-	[20]	0.27±0.06
Ω^-		
Σ		
⋮		
Charge of characteristic π	[20]	Multiplicity: 3.59±0.03±0.07
(not from Λ, K_S)		
Characteristic event topology		

TABLE IV. A few representative modes and their interferences $Im\lambda$ given in terms of the angles of the unitarity triangle. Here $\theta_c \approx 0.22$.

Mode	$Im\lambda$
$B_d \to J/\psi K_S$	$\sin(2\beta)$
$B_d \to \pi^+\pi^-$	$\sin(2\alpha)$
$B_s \to D_s^+ D_s^-, J/\psi\phi$ [49]	$2\,\theta_c \mid V_{ub}/V_{cb} \mid \sin\gamma$